SCIENCE FOR CERAMIC PRODUCTION

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POROUS PERMEABLE CERAMICS FOR FILTER ELEMENTS CLEANING HOT GASES FROM DUST

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The filtering characteristics (air permeability, efficiency) of porous permeable ceramic materials with different microstructures are determined. The requirements on ceramic filter elements are formulated; specifications for a module-type plant with ceramic filter elements are prepared. The use of these elements for cleaning hot gases from dust, apart from the ecological effect, yield an economic effect manifested as additional energy produced due to recovery of waste gas heat.

Contemporary production is impossible without technological processes that yield a required product, but are accompanied by a negative impact on the ambient medium, which reaches a dangerous level and is capable of inflicting irreversible changes in nature. In these processes a huge amount of heat is released into the atmosphere via dust-laden hot gases, whose recycling could substantially raise the economic effect of thermal machines and the efficiency of energy consumption.

The temperature of dust-laden hot gases generated by various technological machines can reach 1000 – 1100°C. Economically, it would be convenient to use the high-energy potential of hot waste gases in recovery boilers for producing overheated steam or in gas turbines for producing electricity [1, 2]. However, the dust contained in hot gases results in a rapid failure of any heat recuperators and the problem remains unsolved.

In practice two types of equipment are used to clean waste gases from dust: bag filters and electric filters. Before dust-laden hot gas is transferred to this equipment for cleaning, it has to be cooled, since bag filters and electric filters cannot operate at high temperatures.

Two methods of cooling are used in the industry.

The first method is evaporative chilling by spraying water (wet cleaning). This method requires circulating water supply and a system for removing solid particles from hundreds of thousands cubic meters of water. Furthermore, large areas of land have to be used for slurry sumps, which have to be treated as well. Moreover, using this method of gas cleaning, a precise temperature of the gas has to be maintained at the exit from the cooling system, preventing its excessive decrease, since this may cause condensing of acid mist due to the low dew point of the gas, which, in turn, abruptly decreases the efficiency of the cleaning equipment [3].

The second method is cooling hot gas by diluting it with cold air (dry gas cleaning). In this method, hot gas is diluted with cold air taken from the ambient atmosphere. In this way the volume of cooled gas to be purified increases manifold, which decreases the efficiency of gas cleaning and requires high energy consumption for removal and emission of gases [4].

The filtering equipment surpasses other types of dust-collecting systems in the efficiency of purifying gas from suspended particles and in its cost effect. The advantages of this method are as follows:

– a high degree of cleaning of gases compared to other purifying devices;

– the possibility of collecting particles under any pressure of the gas flow;

– a high degree of purification at any concentrations of suspended particles in the polluted gas;

– the possibility of full automation of the gas-cleaning process;

– steadiness of the cleaning process and lower dependence on the variation of the physicochemical properties of particles cooled and gas flow rate than in other purification methods.

However, the possibility of using this method for cleaning hot gas without its substantial cooling is now significantly limited by the service parameters of the materials used

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in filtering elements, which have to operate at high temperature under the eroding effect of dust particles and the corrosive effect of aggressive liquid vapors. Thus, the service temperatures of synthetic fabrics commonly used as filtering elements is not higher than 250°C and that of fiber glass fabric not higher than 300°C.

Cooled cleaned gases have low enthalpy and, consequently, the use of any recuperators for recovering heat from these gases becomes economically ineffective.

Therefore, the ecological and economical factors stimulate the development of filter elements from materials capable to perform under increased temperatures. The list of such materials, unfortunately, is limited: porous metals, glass, or ceramics.

Filter elements made from porous permeable metals have not found wide application, since due to the oxidation of particle surface, which is very intense under high temperatures, the permeability and strength of the material decreases. Furthermore, such materials have low corrosion resistance to the vapors of aggressive liquids contained in hot gases. The experience in the use other materials, such as porous glass or ceramics, in gas cleaning in Russia is limited and mainly restricted to testing experimental samples of sintered powders [5]. Yet the world practice shows that the use of porous permeable ceramic materials ceramics in filter elements for the purpose of cleaning hot gases from dust is not only promising (RF patent No. 2163833, U.S. patent No. 4968467), but such elements are actually used in gas-cleaning elements (U.S. patent No. 5460637).

Filter elements of porous permeable ceramics have certain advantages over filters made of other materials [6]:

– high service temperature and high thermal resistance;
– enhanced erosion and corrosion resistance [7];
– resistance to vibration and acoustic loads;
– the possibility of simultaneous cleaning of gas from dust and nitric oxides.

Porous permeable ceramics that can be used for producing filter elements constitute a special class of ceramics with enhanced permeable porosity that is artificially developed by special techniques and controllable pore size and pore size distribution. This class of materials according to the topological principle can be split into two groups: materials with organized and disorganized microstructure.

The first group includes materials made of powders, fibers, or both. Products can be produced from such ceramics by molding or slip casting with subsequent drying and sintering. If needed, machine treatment is possible after firing. The microstructure of such materials, despite certain statistic regularities, is formed by a random distribution of structure-forming elements (powder particles, fibers). Permeable materials made of powders have open porosity of 20 – 45% and pore size of 5 – 400 μm, and fiber-based materials have 30 – 90% open porosity and 5 – 200 μm pore size.

The second group includes materials with a mesh, cellular, or honeycomb structure, i.e., their microstructure is arranged according to a preset algorithm. Mesh-structure materials are made from ceramic fibers on textile or knitting machines; their open porosity is 20 – 80% and pore size 20 – 200 μm. These materials have not found wide application due to their fast aging under the effect of high temperatures and rapid destruction in regeneration of filtering elements by inverse blowing using compressed air. Cellular permeable materials are made by ceramic slip impregnating a cellular foam-polyurethane matrix with open porosity of 75 – 95% and pore size of 200 – 5000 μm [8]. Permeable cellular materials are produced by extruding plastic ceramic mixtures of powders or powders mixed with fibers via a specially designed die; after that the preform is dried and fired. The porosity of such materials is 50 – 80% and the size of the channels that usually have a square section is 800 – 7000 μm.

The purpose of our study is to investigate the possibility of applying various types of porous permeable ceramics (with different microstructures) to gas cleaning.

The experiments were performed on disk-shaped samples of diameter 60 – 62 and thickness 8 – 23 mm. Powder samples 1 – 8 (Table 1) were prepared as follows. We took narrowly fractionated powders of different sizes (electrocorundum, disthene-sillimanite) and introduced the technological binder (clay) and the temporary technological binder (distillers' spent grains slop). The resulting mixture (moisture 7 – 8%) was used to mold samples on a hydraulic press by semidry molding; after drying, the samples were fired at a temperature of 1300 – 1350°C. In order to modify the porous structure, finely dispersed electrocorundum was added to sample 5 and aluminum was introduced in sample 6. To modify hydraulic parameters, a permeable membrane coating was deposited on samples 7 and 8 after firing; then the samples were fired at the same temperature as the samples without coating. Permeable ceramic samples 9 and 10 of silicate fiber were prepared by slip casting in porous permeable molds. Finely milled fiber together with the technological binder, sintering additives, and the temporary binder (polyvinyl alcohol) was used to prepare a fluid suspension (moisture 50%). The molding method provided for the vacuum removal of excessive moisture. Then the samples were dried and fired at a temperature of 1250 – 1300°C.

Samples of permeable cellular ceramics 11 and 12 were prepared by ceramic slip impregnating a cellular polymer matrix made of permeable porous foamed polyurethane. Excessive slip was removed by compression of samples, after which they were dried and fired at a temperature of 1320 – 1350°C.

The properties of samples, such as open porosity, apparent density, and compressive strength (Table 1) were determined in accordance with the measurement methods accepted at the Bacor Scientific Center based on the respective state standards. The mean pore size was determined using computer processing of images obtained with an electron microscope.

TABLE 1

Sample	Characteristics of sample						
	before firing			after firing			
	component	degree of dispersion, µm	content, %	open porosity, %	apparent density, g/cm^3	compressive strength, MPa	mean pore diameter, µm
1	Disthene-sillimanite	200 – 315	85	27.5	1.95	50.0	50 – 70
	Clay	< 2	15				
2	Disthene-sillimanite	100 – 200	85	28.1	1.98	75.0	30 – 50
	Clay	< 2	15				
3, 4	Electrocorundum	40 – 50	85	39.5	2.29	110.0	12 – 16
	Clay	< 2	15				
5	Electrocorundum	40 – 50	75	37.0	2.38	100.0	10 – 12
	Electrocorundum	10 – 14	10				
	Clay	< 2	15				
6	Electrocorundum	40 – 50	75	40.0	2.32	116.0	8 – 10
	Alumina*	–	10				
	Clay	< 2	15				
7	Substrate:						
	electrocorundum	40 – 50	85	–	–	–	12 – 16
	clay	< 2	15				
	Membrane:						
	electrocorundum	20 – 30	90	43.5	2.20	–	10 – 15
	clay	< 2	10				
8	Substrate:						
	electrocorundum	40 – 50	85	–	–	–	12 – 16
	clay	< 2	15				
	Membrane:						
	electrocorundum	2 – 4	90	45.0	2.17	–	2 – 3
	clay	< 2	10				
9, 10	Silicate fiber						
	Binder	2 – 5	98	80.0	0.20	–	10 – 15
		–	2				
11, 12	Cellular ceramics:						
	electrocorundum	10 – 14	75	90.0	0.30	0.8	2 – 3**
	clay	< 2	25				

* Specific surface area 6000 m^2/g.

** In millimeters.

The filtering properties of porous ceramics were studied in accordance with the method in [9] under low gas flow velocities typical of the filtration process, when the prevailing mechanisms in the precipitation of suspended particles (drops) are diffusion and catching (contact). The dispersion composition of mist drops at the entrance to the filter is characterized by the following parameters: median diameter of drops 1.3 µm, mean standard logarithmic deviation of drop-size distribution function 0.23, and drop density 0.885 g/cm^3. The concentration of drops at the entrance to the filter varied within the limits of 500 – 1000 mg/m^3. The measurement results are indicated in Table 2.

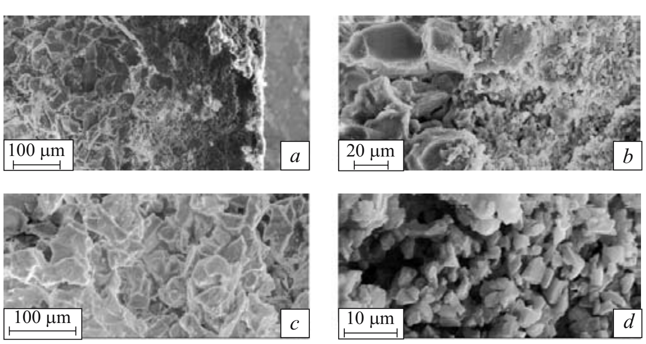

Fig. 1. Microstructure of porous permeable ceramics based on powder with a membrane coating (sample 8): *a*, *b*) substrate with the membrane; *c*) substrate; *d*) membrane; *a* – *c*) fracture; *d*) surface.

The difference in the nature of the initial components and their quantity and morphology determines their different macrostructures (Figs. 1 – 3). A decrease in the dispersion of powder in materials containing a filler of the same fraction (samples 1 – 4) regularly decreases the average pore size and, accordingly, increases their hydraulic resistance. The introduction of a second more dispersed filler fraction (samples 5 and 6) raises even more their hydraulic resistance, although the gas-cleaning efficiency grows as well, which is related to the modified pore structure. Applying a membrane coating (samples 7 and 8) made of narrow-fractionated pow-

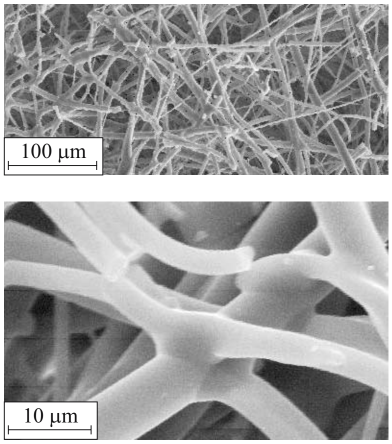

Fig. 2. Microstructure of porous permeable ceramics based on fiber (samples 9 and 10).

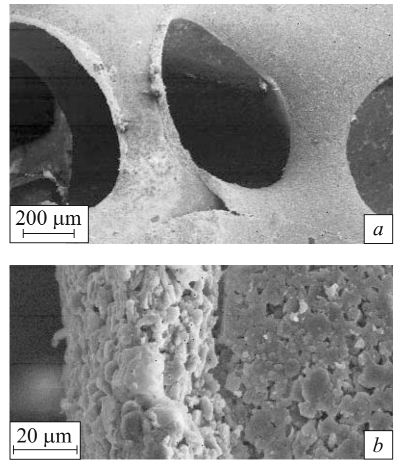

Fig. 3. Microstructure of porous permeable ceramics (samples 11 and 12): *a*) general view of the sample; *b*) microstructure of bridges.

der further increases the hydraulic resistance of these materials. Materials made of silicate fiber (9 and 10) ensure low values of hydraulic resistance and high purification efficiency. Cellular permeable materials (11 and 12), due to their microstructure specifics, have low hydraulic resistance and low gas-cleaning efficiency.

The pore size of permeable materials depends mainly on the size of the particles (fibers) in the initial materials. For equal sizes of the initial materials, the largest average pore sizes are typically registered in fiber materials. In all cases the material of the filter element must have maximum permeability to ensure minimal pressure losses in the filtration medium. The permeability of a porous material grows with increasing pore size, with decreasing pore tortuosity, and with decreasing roughness of the pore surface. Other conditions being equal, porous materials based on smooth fibers have the highest permeability.

Based on laboratory studies performed, we have formulated requirements on filter elements made of porous permeable ceramics [6], developed design specifications for a filtering plant, and prepared design blueprints for the module-type plant FKI-45 plant (Fig. 4) with ceramic filter elements (Fig. 5).

Main Specifications of FKI-45 Filtering Plant for Cleaning Hot Gases

Output of purified gas, m^3/h, at most 4800
Filtration surface area, m^2, at least 45
Specific gas load per filtering surface,
$m^3/(m^2 \cdot min)$, at most 1.8
Hydraulic resistance, Pa, at most:
of filter elements 1800
of filters 2000
Temperature of polluted gas at the entrance
to the filter, °C, at most 1000

TABLE 2

Sample	Thickness, mm	Hydraulic resistance, Pa, under filtration rate, cm/sec								Air permeability, $dm^3/(m^2 \cdot sec)$	Purification efficiency
		1.0	1.5	2.0	3.0	4.2	5.0	7.0	10.0		
1	10	20	30	40	60	–	160	300	520	27.63	0.334
2*	11	340	450	720	1020	–	2300	–	–	0.46	0.502
3	9	320	350	530	780	–	1360	2180	3260	4.61	0.938
4	10	500	620	860	1200	–	2060	3220	–	0.92	0.980
5**	8	480	650	870	1250	–	2140	–	–	0.46	0.949
6	9	950	1100	1600	2200	3200	–	–	–	0.46	0.985
7	8	240	300	430	600	–	1070	1700	2530	9.21	0.961
8	11	1310	1600	2250	3100	4470	–	–	–	0.92	0.827
9	15	< 10	< 10	< 10	10	–	30	40	80	55.26	0.771
10	23	80	100	110	150	–	300	450	710	16.58	0.946
11	15	< 10	< 10	< 10	< 10	–	< 10	–	–	92.10	0.420
12	23	< 10	< 10	< 10	< 10	–	< 10	< 10	< 10	82.89	0.523

* Hydraulic resistance under filtration rate of 5.9 cm/sec is equal to 3160 Pa.

** Hydraulic resistance under filtration rate of 6.8 cm/sec is equal to 3200 Pa.

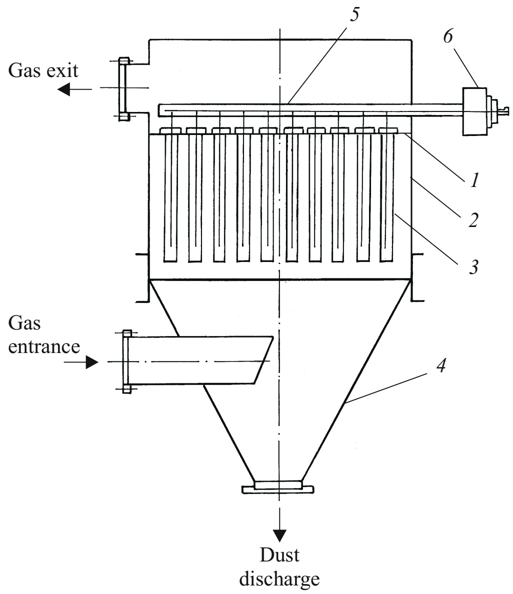

Fig. 4. Diagram of FKI-45 plant with ceramic filter elements: *1*) body; *2*) hopper; *3*) dividing grid; *4*) filtering ceramic element; *5*) supply pipe; *6*) valve section.

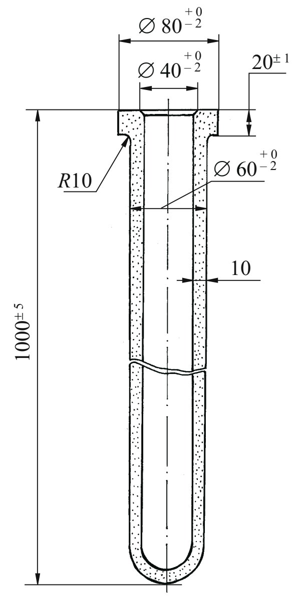

Fig. 5. Ceramic filter element to clean hot gas from dust.

Gas rarefaction in filter, MPa, at most	0.008
Estimated pressure in filter body, MPa, at most	0.1
Mass concentration of dust in the gas, g/m^3,* at most:	
at the entrance	20
at the exist	0.001
Overall dimensions, mm, at most	2400 × 2100 × 2700
Weight, kg, at most	2000

* Calculated for normal conditions.

As a consequence of the studies performed, a new type of a filtering plant with ceramic filter elements has been developed to clean hot waste gas flows from dust. The environmental aspect of this project is obvious, as it prevents emitting toxic compounds into the atmosphere. The economic effect of the project can be illustrated by the following example. A depleting furnace at the Norilsk Nickel company emits 33,000 nm^3/h of dust-laden gas at a temperature of 800°C. The calculation shows that after the hot gas is purified in the FKI-45 filtering plant and supplied to the recovery boiler, it generates 50.5 tons/h of hot steam at a pressure of 4.5 MPa and a temperature of 390°C, which is equivalent to the production of 40 Hcal/h additional energy.

Thus, the use of porous permeable ceramics for filter elements in plants for cleaning hot gases from dust, besides the ecological benefit, yields a direct economic effect manifested in the production of additional energy due to recovery of heat from cleaned hot waste gases. Furthermore, it should be noted that applying catalysts on the porous surface of the filter elements can intensify the environmental effect, as it ensures additional purification of hot gases from vapors of dangerous elements.

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